Hydraulic conductivity reduction due to ponded hog manure

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Maulé, C.P., Fonstad, T.A., Vanapalli, S.K. and Majumdar, G. 2000. Hydraulic conductivity reduction due to ponded hog manure. Can. Agric. Eng. 42:157-163. Results are presented from a study concerning the reduction in soil hydraulic conductivity due to ponded hog manure. Of specific interest is how much of the reduction is 'at the soil surface' as opposed to within the soil. Seven different soils with clay contents ranging from 9 to 33% were studied using 200 mm long soil columns in a low-temperature (5-6°C) environment. Hydraulic conductivities, as measured with water, ranged between 3.0 x 10^{-6} and 1.3 x 10^{-4} m/s before manure application. Fresh hog manure was ponded on these soil columns for a period of 634 days. Hydraulic conductivity, for all soils, decreased rapidly to about 1.0 x 10^{-9} m/s and maintained this value except during the time of failure of the cooling system. A black layer was observed to have developed at the manure-soil interface of all columns within 36 hours of manure ponding. Visual observations conducted between days 136 and 618 showed that the black layer grew downwards into the soil at a rate of 0.3 mm/month. The hydraulic conductivities of the soils at different depth intervals indicated that, most, if not all, of the reduction occurred at the black surface layer. At the end of the 634 day period, the black layer was removed and soil hydraulic conductivities were measured once again using a prepared chemical solution of similar ionic concentration to that of manure. The hydraulic conductivities of all soils increased to that of 'pre-manure' conditions. The results of this study suggest that the hydraulic conductivity reduction from ponded hog manure under these experimental conditions is mainly related to the development of the black layer at the manure-soil interface. Keywords: earthen hog manure, storage structures, hydraulic conductivity, clogging effects.

Les résultats d'une étude portant sur la réduction de la conductivité hydraulique du sol causée par l'application de lisier de porc sont présentés. L'intérêt spécifique concerne le degré de réduction à la surface du sol plutôt qu'à l'intérieur du sol. Sept différents types de sol ayant des contenus en argile variant de 9 à 33% ont été utilisés, utilisant des colonnes de sol d'une longueur de 200 mm dans un environnement à basse température (5-6°C). Précédant l'application de lisier, les conductivités hydrauliques telles que mesurées avec de l'eau variaient entre 3x10^{-6} et 1.3x10^{-4} m/s. Le lisier frais était appliqué sur ces colonnes de sol pour une période de 634 jours. Pour tous les sols, la conductivité hydraulique diminuait rapidement à environ 1.0x10^{-9} m/s et cette valeur était maintenue sauf en cas de mauvais fonctionnement du système de refroidissement. Une couche noire se développait à l'intérieur d'une période de 36 heures suivant l'application du lisier. Des observations visuelles conduites entre les jours 136 et 618 montraient que la couche noire se développait de manière descendante à l'intérieur du sol à une vitesse de 0.3 mm/jours. Les conductivités hydrauliques des sols à différentes profondeurs indiquaient que la plupart, sinon toute réduction se présentait dans la couche noire de surface. À la fin de la période de 634 jours, la couche noire était retirée et les conductivités hydrauliques étaient nouvellement mesurées, utilisant une solution chimique préparée de concentration ionique similaire à celle du lisier. Les conductivités hydrauliques de tous les sols étaient augmentées comparées à celles des conditions pré-lisier. Les résultats de cette étude suggèrent que la réduction des conductivités hydrauliques du lisier de porc compacté sous ces conditions expérimentales est principalement reliée au développement de la couche noire à l'interface lisier-sol.

INTRODUCTION

Earthen manure storages offer an economically viable means of storing manure as compared to concrete or steel tanks. Ground water contamination is a concern if improper soil materials are used or if improper construction techniques are utilized. Barrington and Broughton (1988) published guidelines for selecting soil materials for earthen manure reservoirs based upon optimum sealing conditions. They recommended a minimum soil clay content of 15%, as based on an effective void diameter as achieved by compaction, to achieve "final" infiltration rates of 5 to 10 x 10^{-9} m/s under ponded hog manure. This "final" infiltration rate is apparently a result of the effect of a manure solids mat forming at the soil surface. As a result of this research, several regulatory agencies adopted the use of a minimum of 15% clay content (Manitoba Agriculture 1994; OMAFRA 1994; SCS 1993), and a "final" hydraulic conductivity of 10^{-9} m/s (Manitoba Agriculture 1994; OMAFRA 1994). The Soil Conservation Service (SCS 1993) gives the most complete guide to what soil types and profiles are recommended for construction of manure storages. In addition to a minimum clay content, they recommend a plasticity index of > 10.

Investigators have reported seepage reduction due to sealing of soils by animal manure and by other organic liquids. Davis et al. (1973) studied the infiltration rate of a pond holding liquid dairy manure. The hydraulic conductivity of a newly constructed pond decreased from 1.0 x 10^{-5} m/s to 6.0 x 10^{-8} m/s when water in the pond was replaced with liquid dairy manure. Several studies investigated the sealing effects due to liquid cattle manure and found that the hydraulic conductivity dropped to 1 x 10^{-9} m/s (Culley and Phillips 1982) or the infiltration rate was reduced to 1x10^{-9}m/s (Miller et al. 1985; Rowzell et al. 1985). Barrington et al. (1987a, 1987b), using column tests with liquid hog manure, showed that the final infiltration rates approached values of between 1.0 x 10^{-8} m/s and 1 x 10^{-9} m/s for soils with varying textures. The hydraulic conductivity values decreased approximately two orders of magnitude for all types of soils irrespective of the manure type.
Table I. Physical, mineralogical, and chemical properties of soils used in column study (Fonstad 1996).

<table>
<thead>
<tr>
<th>Soil</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>E clay (%)</th>
<th>SA (m$^2$/g)</th>
<th>Op moist (%)</th>
<th>CEC (Cmol/kg)</th>
<th>Ip (%)</th>
<th>Bd (Mg/m$^3$)</th>
<th>Efv (μm)</th>
<th>pH</th>
<th>EC (mS/cm)</th>
<th>SAR</th>
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<td>33</td>
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<td>12</td>
<td>20</td>
<td>6</td>
<td>10.7</td>
<td>5.8</td>
<td>9</td>
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<td>9</td>
<td>80</td>
<td>31</td>
<td>12.6</td>
<td>6.4</td>
<td>NP</td>
<td>1.58</td>
<td>0.64</td>
<td>8.1</td>
<td>2.2</td>
<td>2.7</td>
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</table>

E clay: expanding clay, expressed as a percentage of clay fraction (expanding clay percentage was approximated from X-ray analysis done by A. Mermut, University of Saskatchewan, Saskatoon, SK)

SA: surface area of the clay fraction.

Op moist: optimum moisture content from standard Proctor Analysis expressed on mass basis.

CEC: Cation Exchange Capacity of the entire soil.

Ip: plasticity index (NP is not plastic).

Bd: dry bulk density.

Efv: effective void diameter (Barrington and Broughton 1988).

EC: electrical conductivity of the saturated paste extract. EC and Na$^+$ were determined from the saturated paste extract of the soil and corrected for the saturated moisture contents of the columns.

SAR: Sodium Adsorption Ratio of the saturated paste extract.

Chang et al. (1974), deTar (1979), Rowsell et al. (1985) and Barrington et al. (1987a, 1987b) demonstrated that the sealing mechanism in soils under ponded manure conditions is a physical blocking of pores by the particulate material in the manure. However, other researchers demonstrated that clogging under ponded conditions (not necessarily manure) can be due to microbial activity and polysaccharide accumulation in the soil (Allison 1947; McCalla 1950; Avnimelech and Nevo 1963; Mitchell and Nevo 1963; Chang et al. 1974; Nicholaichuk 1978; McConkey et al. 1990). Chang et al. (1974) and de Vries (1972) reported that clogged soils, if allowed to dry, could recover to initial hydraulic conductivity values or higher within 8 to 125 days of drying, when tested with water.

More studies are necessary to better explain the mechanisms and the durability of the flow reduction with ponded waste water. The study reported in this paper furthers the investigation into flow reduction due to ponded hog manure with respect to the following specific questions:

1. By how much is flow reduced?
2. Does soil texture have an effect on flow reduction?
3. Does length of time of manure ponding have an effect on flow reduction?
4. How much of the flow reduction is due to soil surface effects (as opposed to clogging within the soil)?
5. What is the durability of the flow reduction?
6. What is the effect on flow rates when the surface layer is removed?

Flow rates and hydraulic heads with depth were measured on seven different Saskatchewan subsoil materials using soil columns ponded with hog manure for a period of more than 600 days. Hydraulic conductivities of the columns and individual layers were calculated. Visual analysis was also conducted with close-up photography through the acrylic walls of the columns and with thin soil sections. It is expected that the results presented in this paper will be useful for providing better guidelines in the design and construction of earthen hog manure storage structures.

MATERIALS and METHODS

Soil properties and setup of soil columns

Seven different Saskatchewan soils were collected from subsoil materials at a depth of 3 m below natural ground level (Table I). Three replicates of columns for each soil were prepared and packed into transparent acrylic cylinders that were 900 mm in length with a 120 mm inside diameter (Fig. 1a). An acrylic base with a tube connector fitting was attached to the bottom to collect outflow. A 30 mm support base of coarse sand was first established at the bottom of the soil columns. Each soil was air dried, ground, and sieved to remove particles greater than 2 mm size. The prepared soil was then moistened to its optimum moisture content (Table I), as determined from Standard Proctor Density (ASTM D-698-91), and compacted into the acrylic cylinder in 50 mm layers. The final thickness of the soil layers was 200 mm. Final dry densities of the soil columns ranged between 90 and 92% of Maximum Standard Proctor Density for each layer resulting in bulk densities between 1.50 and 1.83 Mg/m$^3$. Low compactive efforts were used to simulate field compaction conditions easily achieved by traffic of excavation equipment (SCS 1993). The soil surface of each compacted layer was scarified with a wire brush such that flow properties of the compacted soil would not be influenced by any discontinuities within the sample. The column design as shown in Fig. 1a is after Barrington et al. (1987b).

Three manometers were installed by horizontal insertion of an 80 mm long, 8 mm diameter stainless steel tube with 2 mm diameter holes drilled along the length. Tubes were inserted at the soil surface, at 25 mm, and at 100 mm beneath the soil surface (Fig. 1a). The prepared columns were set up in a temperature-controlled room at approximately 6°C in order to minimize biological effects. This temperature value also represents the year-round average for shallow groundwater systems in Saskatchewan. At various time intervals during the 634 days testing period, replicates of each soil were disassembled for chemical, visual, and microscopic analysis.
Experimental procedure for measurements

The soil columns were first saturated for a period of two weeks with tap water. The saturated hydraulic conductivity of the entire soil column was then measured under steady state conditions using a constant head of water under the conditions shown in Fig. 1a.

Fresh hog manure from local pen gutters with a total N of 6100 mg/L, an electrical conductivity of 39 mS/cm, and the following dissolved ion concentrations: NH₄⁺, 4560 mg/L; K⁺, 2900 mg/L; Na⁺, 610 mg/L; Ca²⁺, 120 mg/L; Mg²⁺, 24 mg/L; Cl⁻, 4550 mg/L; and SO₄²⁻, 300 mg/L was placed on the saturated soil columns after removing the ponded water. Flow rates reduced rapidly after adding manure and within 48 hours the manometers did not contain any fluid. It was concluded that the column had become desaturated from air entering through the manometers because of the presence of a low permeability layer at the soil surface. A very thin black layer (less than 1 mm) was visible at the soil surface. The system was resaturated on the third day with water. This was achieved by increasing the head at the outlet to a greater pressure than the ponded manure at the soil surface. After the manometers were re-established the outlet tube was lowered to a new configuration (Fig. 1b) where the outlet pressure was equivalent to the height of the soil surface above the outlet. After a period of 35 days the manometer levels were stabilized and the columns were judged to be properly resaturated. Hydraulic conductivity determinations then commenced through measurement of outflow rates and manometer levels. For the first six months, measurements were taken on a weekly basis, thereafter on a biweekly basis. Raw supernatant from the liquid hog manure, stored in 20 L pails at 6°C, was applied to the top of the column to maintain a ponded depth of 50 mm and the following makeup: KCl (4.0 g/L), NaCl (2.0 g/L), CaCl₂·H₂O (2.0 g/L), and (NH₄)₂SO₄ (6 g/L).

Determination of hydraulic conductivity

All hydraulic conductivity determinations were done with the column setup as described by Fig. 1b. The saturated hydraulic conductivity (Kₛ) of the entire soil length (i.e. 200 mm) and of the manure seal was determined under steady seepage conditions using Darcy’s law. The hydraulic gradient was determined based on the ponded manure depth and by assuming that the sand base had negligible resistance. This hydraulic conductivity is referred to as the total hydraulic conductivity, Kₛ. Manometer measurements made it possible to determine the Kₛ of the four different layers in the soil columns. The hydraulic gradient, and thus the hydraulic conductivity, for the black surface layer was determined from measurements of the ponded depth of manure and the manometer placed at the soil surface. The assumption being that any clogging caused by the settlement of manure solids at the soil surface would also affect the manometer at the soil surface. The effective hydraulic conductivity of the entire column, Kₑf, was calculated using:

$$K_{\text{ef}} = \frac{L_1 + L_2 + L_3 + L_4}{L_1 / K_1 + L_2 / K_2 + L_3 / K_3 + L_4 / K_4}$$

where:

- L₁ = thickness of manure seal at the soil surface (mm),
- L₂ = distance between the soil surface and a depth 25 mm (mm),
- L₃ = distance between the manometers at 25 mm and 100 mm (mm),
- L₄ = distance between the manometer at 100 mm and the bottom of the soil at 200 mm (mm), and
- K₁, K₂, K₃, K₄ = saturated hydraulic conductivity for the respective layers (m/s).
Fig. 2. Average hydraulic conductivities of soil depth intervals and the entire soil column (3 replicates for each soil type) for water (a) and for manure (b). For (b) measurements were taken weekly between day 38 and day 185.

The thickness of the manure seal was measured visually through the acrylic columns. The comparisons of $K_{sat}$ to $K_{eff}$ and the saturated hydraulic conductivity of individual layers were useful determinants of the effect of surface sealing and pore clogging on overall flow reduction.

Visual and microscopic analysis

Studies of thin sections studies were undertaken to evaluate pore structure, black surface layer formation, and clogging within the soil. To prepare the thin sections for analysis, the samples had to be air-dried, impregnated with a resin, cut with a diamond saw, ground, and polished. The final section, as mounted on a glass slide, was 65 x 85 mm and 30 μm thick. Two vertical thin sections were prepared for each column tested, one from the top of the core and another from the bottom of the core. Thin sections were examined with a 30X Zeiss Polarized microscope and photographic enlargements. Further details related to sample preparation and thin sectioning are available from Majumdar (1997).

Differences in the color of the soil and in the soil-manure interface at various time intervals were captured by digitizing photographs which were taken by a 35 mm camera using a close-up lens. Seal development relative to reference marks was measured to determine the change in thickness with time. At least three separate measurement points for each column were used. Small samples were taken at the manure-soil interface from soils #1, #4, and #7 for scanning electron microscopic (SEM) analyses. More details with respect to the above experimental procedures are available in Majumdar (1997).

RESULTS and OBSERVATIONS

Soil hydraulic conductivity without manure

The average column hydraulic conductivity values measured with water varied from $2.6 \times 10^{-8}$ to $131.8 \times 10^{-8}$ m/s (Fig. 2a). There was a close agreement (coefficient of variations were between 8 and 65%) within the three column replicates for each soil. The test results suggest that saturated hydraulic conductivity was largely a function of clay content (Table I). None of the soils had hydraulic conductivities less than $1 \times 10^{-9}$ m/s which was recommended by two reports (Gangbazo et al. 1989; SCS 1993). Brach et al. (1992), in Minnesota, recommended that the measured hydraulic conductivity (with water) be less than $1 \times 10^{-9}$ m/s, while others recommended...
that the infiltration rate (with water) be less than $1 \times 10^{-7}$ m/s (OMAFRA 1994; SCS 1993).

Hydraulic conductivity of the soils with ponded manure

With ponding of manure and the reconfigured column design (Fig 1b), column hydraulic conductivity values decreased to near $0.1 \times 10^{-8}$ m/s and varied within half an order of magnitude of this value for most of the study period (Figs. 2b and 3). The drop occurred regardless of the hydraulic conductivity determined with water and regardless of texture. This behavior is consistent with the research studies of other investigators (Culley and Phillips 1982; Rowsell et al. 1985; Barrington et al. 1987a, 1987b).

The manure seal, which was taken to be 3 mm in thickness at the time of $K_{sat}$ determination for manure ponding (days 38 to 185), had the smallest hydraulic conductivity with a typical value of $0.003 \times 10^{-8}$ m/s (Fig 2b). The 0-25 mm depth interval had the next smallest hydraulic conductivity values. The hydraulic conductivity values for the 0-25 mm depth interval was one to three orders greater in magnitude than the 'seal' hydraulic conductivity value; however, they were about 10 to 20% of that in the deeper soil intervals. The hydraulic conductivity values for the 0-25 mm depth interval were less for ponded manure conditions in comparison to water (Fig. 2).

There was a seven hour failure in the cooling system on day 76 and a one day failure on day 276 causing the room temperature to rise from 6°C to about 21°C. In both cases, air bubbles were found in the outflow tubes. The hydraulic conductivity values increased in the period following the increase in temperature (Fig. 3). The average hydraulic conductivity of all the columns, during days 81 to 102, rose from $0.11 \times 10^{-8}$ to $0.15 \times 10^{-8}$ m/s and then decreased back to their original values within 10 days. For the failure on day 276, the average hydraulic conductivity of all the columns increased from less than $0.10 \times 10^{-8}$ to about $0.36 \times 10^{-8}$ m/s (Fig. 3). Some columns did not recover to their pre-heating hydraulic conductivity values until day 400. The hydraulic conductivity increase, during days 599-634, likely was also due to an increase in temperature as the room was heavily used by people taking apart columns.

Effect of seal removal upon hydraulic conductivity behavior

The effect of removing the manure seal from the soil surface (after day 634) and replacing the ponded manure with a chemical solution resulted in the increase of all hydraulic conductivities back to values originally measured with water (Fig. 4).

Visual and microscopic observations of soil-manure interface

A layer of black amorphous material was observed to develop upon the soil surface in the first 16 hours of the experimental study. The outflow from the columns slowed considerably during this period. Similar observations associated with decreases in hydraulic conductivity of soil columns were reported by other investigators (Rowsell et al. 1985; Barrington et al. 1987a, 1987b). Within 36 hours, the columns containing soils 3 to 7 had distinct black lines with a thickness of less than 1 mm on the soil surface. However, columns containing soils 1 and 2 had diffuse black material forming on the soil surface. Through the use of digitized photographs, the thickness of the black layer was measured over the study period; 17 columns photographed on day 136 of the study, 11 on day 319, 14 on day 403, and 4 on day 618. These photographs showed that the black layer increased at a near constant average rate of 0.31 mm per month, without considering the first 19 weeks. The growth of the seal appeared to be extending into the soil, rather than becoming thicker on top of the soil surface. The regression equation, as calculated from measurements taken from the photographs for this relationship is:

$$T = 0.0104D + 1.585$$

where:

- $T$ = thickness of the black layer (mm), and
- $D$ = number of day manure was ponded on soil surface.

$\left( r^2 = 0.583; n = 46; P < 0.001 \right)$

Fig. 4. Hydraulic conductivities for entire columns (a) and for 25 to 100 mm interval (b) for water, manure, and chemical solutions.
The regression equation is only appropriate for the period covered by the measurements, days 136 to 618. The intercept of 1.585 mm at time = 0 supports the observations of development of the black layer during the first 36 hours.

Seals investigated from soil core disassembly on day 186 were observed to be a fragile black layer that could be separated from the underlying soil. This black layer was observed to disappear upon drying and might have been absorbed into the mineral soil matrix (Majumdar 1997). Just above the seal layer there were identifiable plant parts that formed a manure mat. These observations were from thin section analysis with an optical microscope and SEM analysis. The seal itself could not be thoroughly investigated with these two techniques due to the limitations in pretreatment methods causing drying. Organic particles and coatings within the pores of the soil were found using both these techniques. The presence of organic particles in sandy soils was observed to be more common and frequent. Organic particles were also found to protrude deeper into coarse-grained soils when compared to fine-grained soils (Majumdar 1997). Disassembly of the cores after day 634 showed soil materials within the black layer.

CONCLUSIONS

Experimental results of the research study have shown that reduction in hydraulic conductivity occurs simultaneously with the formation of the manure seal. The hydraulic conductivity values, however, reached original values measured with water once the seal was removed. This phenomenon clearly shows that the reduction in hydraulic conductivity values are associated with the upper thin layer (3 to 8 mm) of the black layer and the soil surface, rather than clogging of the soil pores deeper in the column. The unplanned rise in temperature in the control room during periods of the study appeared to have disrupted the integrity of the seal for short periods. These events resulted in a large increase in flow rates which may be due to the softening of the manure seal, seal disruption by gases, and reduced viscosities of the fluids.

The hypothesis that a very thin surface layer can be the primary controlling factor in the reduction of hydraulic conductivity for the entire column can be shown with the use of a two-layered flow system using Eq. 1. The two layers consist of the manure seal and the soil layer whose hydraulic conductivity values as measured with water are summarized in Fig. 2. Figure 5 summarizes the comparisons of calculated effective hydraulic conductivity value, $K_{\text{eff}}$, for various manure seal layer and soil layer thicknesses.

With the exception of Soil #1, the effective hydraulic conductivity, $K_{\text{eff}}$, increased to about twice the measured manure hydraulic conductivity, $K_{\text{manure}}$, for a manure seal, $D_s$ equal to 3 mm (Fig. 5). A seal thickness of 8 mm reduced the effective hydraulic conductivity, $K_{\text{eff}}$, to a value slightly lower than the measured manure hydraulic conductivity. Note that the overall $K_{\text{eff}}$ also increases with an increase of the soil layer thickness. The seal layer still exerts primary control on the effective hydraulic conductivity behavior even when the thickness of soil layer is 1000 mm as compared to 200 mm. However, the seal begins to lose its effectiveness with increasing penetration of the seepage front.

The hydraulic conductivity values measured in soil columns after scraping off the manure seal suggest that reductions in hydraulic conductivity are primarily caused by the manure seal formation. These results also suggest that the presence of any clogging or coatings in soil pores had little effect on hydraulic conductivity values. However, the formation of a 3 mm seal due to ponded manure in soil columns does not fully account for the total reduction in hydraulic conductivity values.

Several possibilities and scenarios may have to be considered for a rigorous analysis: (1) unsaturated conditions caused by the manure seal on top of the soil surface, (2) unsaturated conditions caused by gas production within the soil column, or (3) temporary clogging of pore spaces by manure particles.

DISCUSSION

The results of this study suggest that the formation of the manure seal is the primary factor for hydraulic conductivity reduction of all the soils tested in a controlled low-temperature environment. The following conclusions can be drawn and answers provided to the questions in the introduction.

1. The flow reduced by two to three orders of magnitude.
2. Texture had little apparent effect upon flow reduction.
3. The amount of time of manure ponding seems to have little effect upon flow reduction.
SUGGESTIONS FOR FUTURE WORK

The above findings were based on studies undertaken in a controlled environment. Several other questions can be raised. Some of which are listed below.

1. Is there a possibility that unsaturated conditions, caused by the accumulation of gas from decomposition processes, could occur beneath the seal?
2. Is there a contribution to seal growth by micro-organisms within the soil?
3. What is the effect of the high ionic strength of the manure upon clay and its soil pore structure?
4. Would any of these observed effects be similar if study temperatures were higher e.g., 12°C or 20°C?
5. What would be the effect of field conditions (i.e., wet-dry and/or freeze-thaw cycles) upon the seal and upon soil permeability?

The experiment described in this paper is a fundamental baseline study. Further research is necessary to answer all the questions listed above and others related to the construction, design, and location of manure structures to provide better guidelines.

ACKNOWLEDGEMENTS

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REFERENCES


